A Flexible Autonomous Power Management System For Small Spacecraft

Ron Dunbar and Gordon Hardman
Orbital Sciences Corporation
3380 Mitchell Lane
Boulder, CO

ABSTRACT

Small satellites have used a variety of methods for regulating battery charge and managing solar power variations, mainly adapted from standard practice on larger spacecraft. A computer controlled power management subsystem is described with advantages for small spacecraft. Small spacecraft must be more parsimonious with power because of mass and surface area limitations. The controller provides separate modes for dealing with this scarce resource in load-limited, solar array-limited and battery-limited regimes. A microcontroller implements the strategies chosen for each regime, and is capable of fully autonomous operation. Algorithms have been developed to allow this controller to implement a self-adjusting digital servo system which continuously seeks to optimize operation. Theory, implementation and results will be presented.

INTRODUCTION

A spacecraft power system must provide continuous power to payloads and service subsystems in an environment where the prime power is routinely interrupted by the eclipse of the source (usually a solar array) by passage through the Earth's shadow. Solar array degradation over time must be taken into account, along with other mission features such as variable solar aspect angles and fluctuating loads.

In small spacecraft the problems associated with power system design are exacerbated due to extreme mass and volume constraints. These constraints mean that certain straightforward remedies, such as sun-tracking solar arrays, heat pipes, and generous radiative cooling surfaces are denied the designer. In addition, the desire to minimize battery mass means that the power system must utilize this valuable resource as effectively as possible.

Fortunately, modern embedded microcontrollers are available which are nearly ideal for use as the power system controller for a small satellite. Also, switchmode convertors are readily designed with high efficiency for transferring power between two points at a different potential. Extensive use is made of these technologies in solving design problems in this application. The result is an elegant high-performance power management system which is readily adapted and scaled to meet many different mission requirements.

CHOICE OF TOPOLOGY

Low earth orbit (LEO) missions are frequent candidates for small satellite designs. These orbits are characterized by their high eclipse ratio of up to 30% or so. Higher orbits tend to be less stressing in this regard, depending on eclipse operational requirements (reduced or full power) and the power level and reliability requirements. The controller described here was designed with LEO requirements in mind, but nothing in it's design precludes use in other orbits.

Power system topologies used to date have been "optimized" for various criteria, frequently mass [1]. The topology presented here was arrived at by using the principle that the number of times energy must be passed through a power convertor should be minimized. Each time a power convertor handles the energy, it extracts an efficiency penalty of around 10-20%. By minimizing energy losses, solar array, battery and thermal system size are minimized, thereby giving a functionally equivalent approach to mass minimization.

The topology is shown in Figure 1. While in sunlight, the solar array energy is used to charge the battery and also to feed the regulator supplying those loads needing accurately regulated supplies. In addition, some loads are connected directly to the battery terminals. These loads must be able to tolerate the normal variation of battery voltage with temperature and state of charge. Experience has shown that some of the largest loads, such as the transmitter high power amplifiers (HPAs) can be placed on this bus; this may require special attention during the design of circuits which will be powered from this bus. In general, as much of the spacecraft power as possible should be drawn from this "partially regulated" bus.

While in eclipse, the "partially regulated" bus continues to supply power to the loads connected to it and, in addition, the battery supplies the fully regulated bus through the (now forward biased) D1.

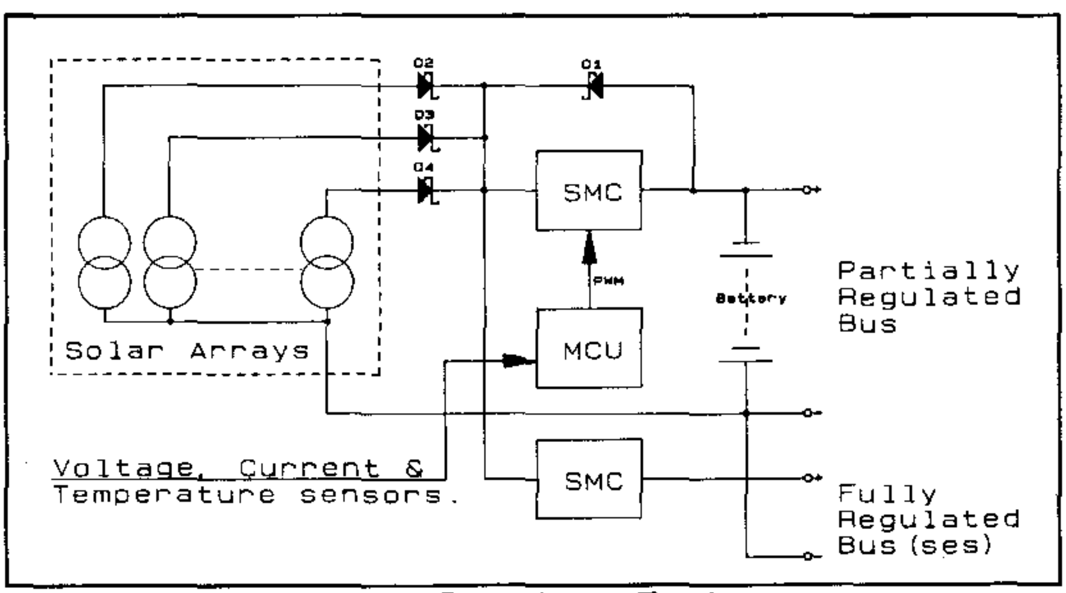


Figure 1. Power System Topology

INTELLIGENT CONTROLLER

Previously, designers of Battery Charge Regulators (BCR) have used such techniques as switching solar arrays in and out, dumping excess power into resistive dissipators, inserting series resistance into the charge path; all resulting (at best) in very coarse control of battery charge current and frequent abuse of solar arrays. As BCR design progressed, techniques such as digital "set-point control" surfaced [2]; this allowed the spacecraft's flight computer to vary the charge rate and the operating point of the solar arrays, but this method could only function in a "preset" mode and management required a considerable amount of attention from the flight computer or, worse yet, intervention from the ground control network.

The designer of a power system for a small, low power spacecraft is unavoidably faced with the ever-present problem of efficiency; the solar panels are always too small and the power demands too large. Efficiency is of utmost importance, and every available milliwatt of power must be usable; heat generated equates to power wasted. With the availability of microcontrollers which can be "embedded" in a BCR, the possibility exists of having a power system which continuously seeks to optimize power availability throughout the lifetime of the spacecraft.

The BCR presented in this paper employs an embedded controller of the 80C51 family; the specific MCU utilized includes the following attributes:

- 2 Pulse Width Modulated outputs.
- 8 multiplexed A/D inputs *(8-bit resolution)*.
- A full-duplex UART for communications with the "host" system via which commands and telemetry are conveyed.
- A synchronous serial port over which communications with a "twin" BCR provides the capability for quadruple redundancy.
- 64K of ROM or EPROM program memory *(internal or external)*.
- 64K of external RAM data memory.
- 512 bytes of internal RAM for flags, stack, 7 register banks of 8 registers each and (never enough) working storage.

Figure 2 (following page) shows the main functional elements of the BCR itself; the solar arrays are connected through Schottky diodes to provide solar panel isolation with minimum power loss. Power is then fed to two Power MOSFETs; P-channel devices are shown, but N-channel logic-level MOSFETs can be utilized with appropriate level shifting on the gates.

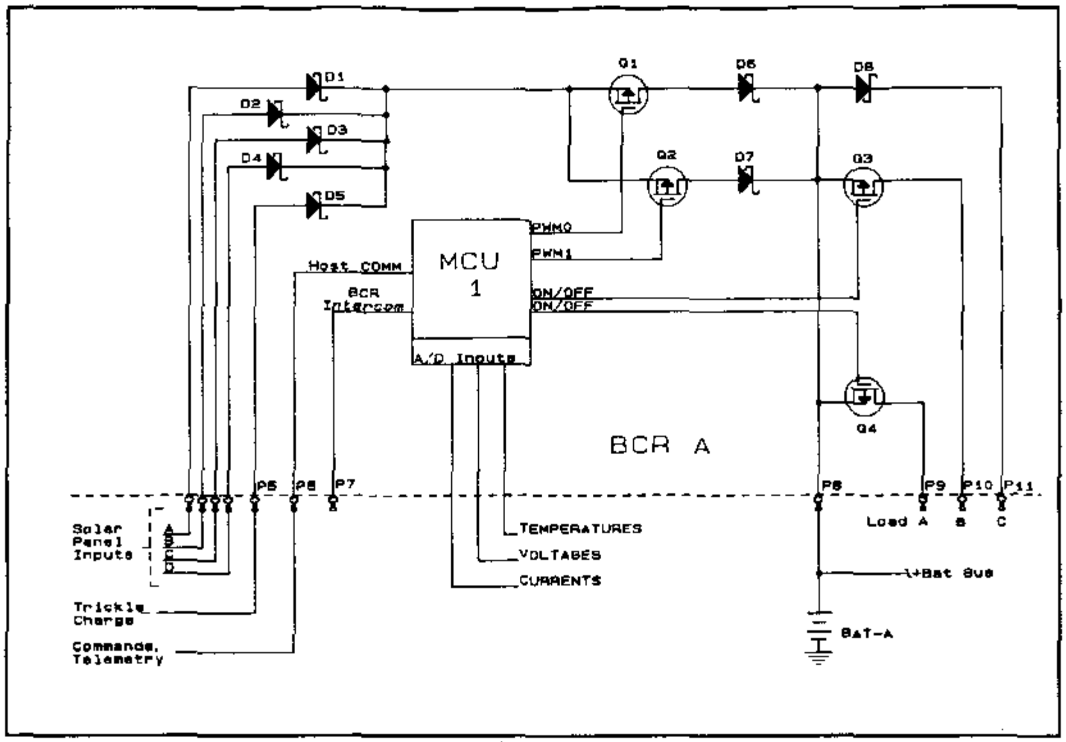


Figure 2. Intelligent BCR Topology

In the configuration shown, the two FETs (Q1 and Q2) provide two distinct charge paths to the battery; only one is used at a time. Since charge-path components are routinely subjected to extremely stressful conditions, redundancy is of great importance here. If Q1 or any of the filter components (not shown) between Q1 and the following diode D6 should fail or degrade, the MCU will detect the anomaly and automatically shut down the Q1 charge path while simultaneously switching in the Q2 alternate charge path, thus maintaining uninterrupted power to the connected loads.

The gates of the two MOSFETs (Q1 and Q2) are controlled by separate PWM outputs from the MCU, allowing smooth control of the FET's duty cycle from 0 to 100% in steps of 0.4% (100/255). To accurately manage the state of charge and the charge rate of the battery, the MCU reads the battery voltage, battery temperature, battery charge/discharge current, array voltage, array current and array temperature approximately once per second, using it's onboard A/D converter. Since battery terminal voltage is dependent on both temperature and charge rate, the MCU applies a correction algorithm to arrive at what the voltage readings would have been if taken at 25 °C. A table of voltage threshold levels (modifiable by ground command and password protected) is then referenced to determine what charge rate is appropriate, based on the battery manufacturer's recommendations and current conditions *(no pun intended)*.

THEORY OF OPERATION

In this application, four distinct charge modes were implemented; (1) **Maximum** *(all the arrays can deliver)*, (2) **Normal** *($\leq C/2.5$, depending on maximum available array output power)*, (3) **Trickle** *($C/22$)* and (4) **No charging.** Hysteresis values are also built into the threshold table to avoid chatter when switching from one charge mode to another.

Since the BCR software is single-mindedly determined to maintain the precise charge rate appropriate for any given set of conditions (which are continuously variable, of course), the effect of transient loads is automatically and promptly compensated for; if a transient load of 1 amp should be abruptly switched on, the current available to charge the battery would correspondingly decrease. The MCU would respond by increasing the duty cycle of the MOSFET switch until the desired charge rate was restored. If the arrays are unable to supply the total load in addition to the "target" battery charge current, then the batteries either receive less than the desired share, or in extreme cases (such as eclipse), the batteries supply the entire demand.

So long as *any* power is available from the solar panels under these conditions, the MOSFET's duty cycle would gradually be increased to 100% by the MCU. If there is *no* power available from the arrays, the duty cycle is reset to 0%, waiting for such time as sunlight again produces power from the arrays. This is done to prevent a stressful inrush of current when exiting eclipse with cold solar arrays; when sunlight is detected by the MCU, it implements a "soft start" by **gradually** ramping the MOSFET's duty cycle upward until the desired level is reached. This same "soft start" action is also performed following a Power ON Reset.

Under conditions which demand maximum power from the arrays, the MCU "hunts" the PWM output, seeking to keep the array's operating point at the optimum "knee" of the power curve. This hunting relieves the need to worry about array temperatures and automatically compensates for solar array aging effects; the arrays will automatically be operated at their optimum point at BOL, EOL and all times between. Happily, this approach also minimizes excess heat generation in the arrays themselves which is a distinct benefit in small satellites where elimination of excess heat is always a difficult problem; one which it's better to *avoid* than to be forced to deal with.

Figure 2 also shows two "load control" MOSFET switches, Q3 and Q4. These are simply switched ON and OFF by the MCU in response to appropriate commands from the host computer or a relayed ground command. The two FETs control Load-A and Load-B, while Load-C is directly connected via another Schottky diode; Load-C is a "critical" load which should never be turned OFF. The Schottky diode is not necessary in this particular configuration, but is required when two BCRs are cross-coupled (to two batteries simultaneously) for redundancy. When a single BCR configuration is used, this diode is replaced by a jumper.

With minimal modification of the BCR software (mostly to the tables) and appropriate strapping of inputs and outputs, the same circuit also serves as a Battery Discharge Regulator (BDR). This makes running the batteries at one voltage and the spacecraft bus at another (either higher or lower) an easy task. Both the BCR and BDR can function in either the "buck" or "boost" mode by appropriate strapping of three components following the MOSFET PWM switch. The addition of FET switches at appropriate points (controlled by the MCU) would allow dynamic switching between buck and boost modes, but circuit complexity would be significantly increased. It is far better to select battery and bus voltage combinations which allow the circuit to always operate in one mode or the other.

Because the 80C51 family of microcontrollers was specifically designed for control applications, the resultant program code is extremely efficient; the code required to implement all the functions for this application amounted to less than 2.5K. This includes the following general tasks which are in addition to the power management functions:

- Recognize and act upon 10 commands.
- Collect and normalize
  6 current measurements,
  2 voltage measurements,
  5 temperature readings.
- Check/generate CRCs for incoming/outgoing message blocks.
  (Using a modified X.25 protocol)
- Generate and transmit limit warning messages to the host computer.
- Generate and transmit a CRC'd 32 byte telemetry block either upon host request, or automatically on a timed basis. (See Appendix A).

PERFORMANCE RESULTS

The first version of the BCR was developed for DATASAT-X. This small spacecraft was equipped with 2 solar panels running at 32 volts with each producing 27 watts (BOL, $\beta = 0$). A 14 volt, 4 AH battery was used. The unit was subjected to environmental tests while in actual operation over extended periods, with excellent results.

The measured overall efficiency of this BCR approaches 87%. This figure was realized by setting a high priority on the selection of every active component in the circuit, consistent with performance, accuracy and reliability. The MCU, current sensor electronics, voltage references, reset controller and all other 'glue' logic consume less than 150 milliwatts when operating with an MCU clock frequency of 11.059 Mhz. Slightly better overall efficiency could be obtained by making use of the MCU's *Idle* and *Halt* modes during eclipse, reducing the BCR's power consumption to extremely low levels during a portion of the orbit.

APPLICABILITY TO OTHER SYSTEMS

The design is readily scalable to other power and voltage levels. To accommodate such changes, minor component modifications are required in the switch mode converters. Since certain of the power losses are fixed, the overall efficiency improves with increasing power throughput.

The design has been proposed as a baseline for spacecraft busses up to a 2KW power level, though operation at high power has not been verified. In addition, since all operating parameters can be software reconfigured, operation with nickel-hydrogen, or even more exotic battery technologies is straightforward.

References

[1] "Satellite Power System Topologies", D. O'Sullivan
ESA Journal, 1989, Vol. 13, No. 3

[2] "The Integrated Housekeeping Unit", G. E. Hardman
Proceedings of the 1st USU Conference on Small Satellites,
Logan, Utah, October 7-9, 1987

APPENDIX A

TELEMETRY, COMMAND and ALERT LIST

TELEMETRY

+Ycur	+Y Solar Panel current	TFETSW	Power MOSFET temp
-Ycur	-Y Solar Panel current	T+Ypnl	+Y Solar Panel temp
ICHG	Battery Charge current	T-Ypnl	-Y Solar Panel temp
I14V	14V Bus current	TBAT	Battery temperature
I+5V	+5V Supply current	VBAT	Battery voltage
I+8V	+8V Supply current	VMSA	Solar Array voltage
TREF	Analog Ref. regulator temp		

(Also, 10 bytes of status points, flags and counters are included in TLM block)

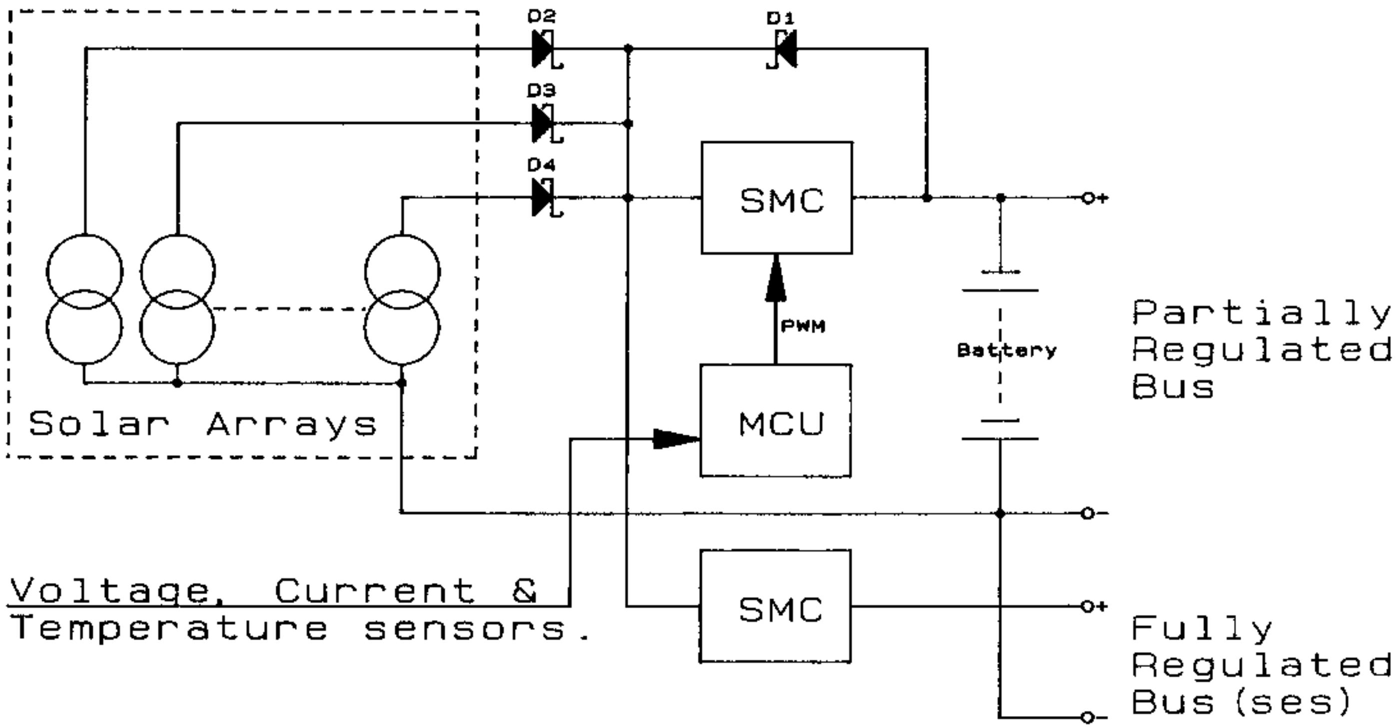
COMMANDS

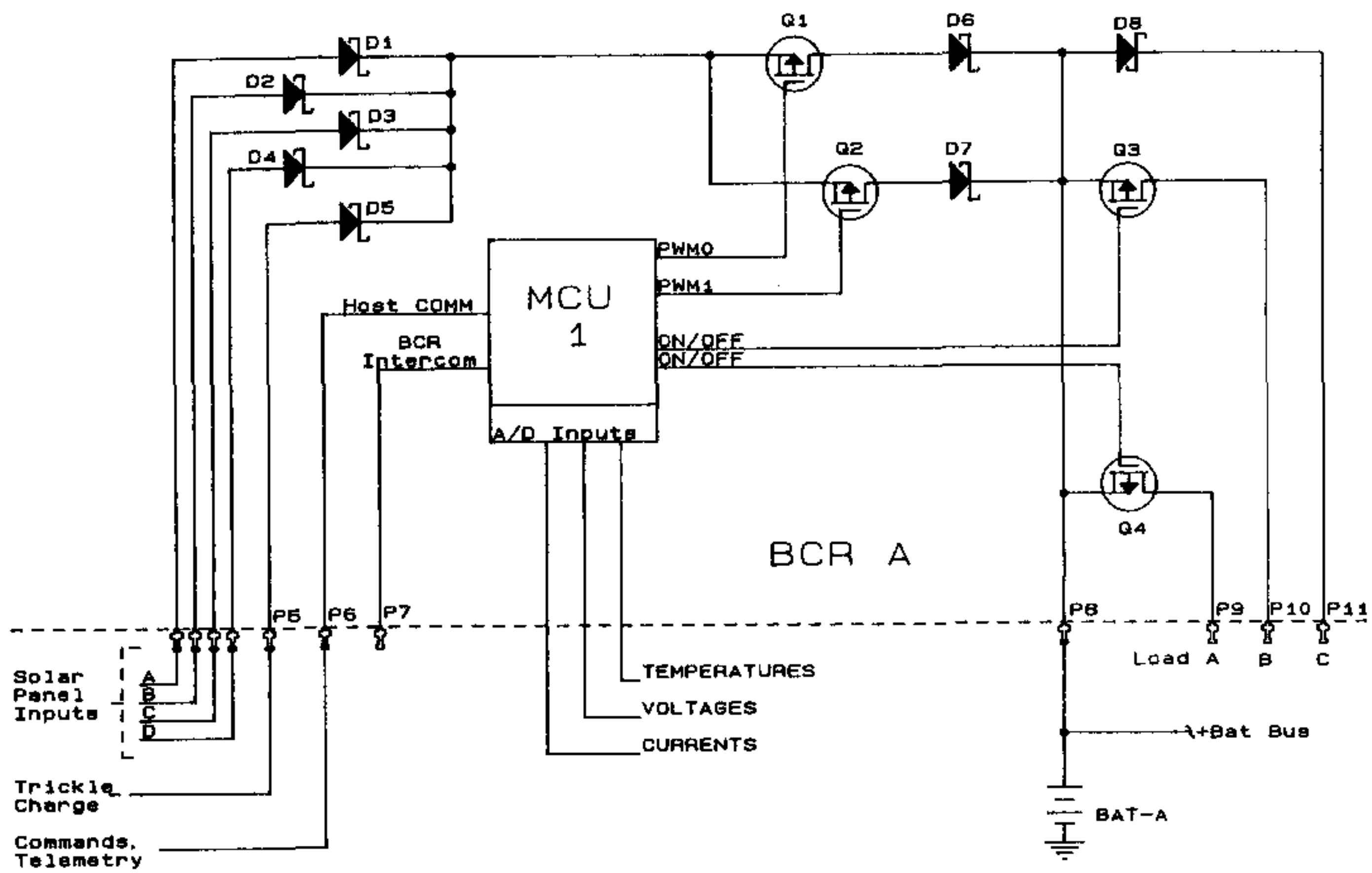
WATCHDOG-ON	Enable the Watchdog timer.
WATCHDOG-OFF	Disable the Watchdog timer *(password reqd)*
RESET_BCR	Reset and Restart *(password reqd)*
CLR_COUNTERS	Reset software counters
BCR_SET	Modify 6 Threshold Table entries *(password reqd)*
QUERY_SETPOINTS	Transmit 6 current Threshold Table entries
AUTO_TLM ON	Enable unsolicited periodic TLM block transmission
AUTO_TLM OFF	Disable automatic TLM transmission
TLM_REQUEST	Assemble and transmit 32 byte TLM block to requestor

ALERTS

UHF_OFF_EMER	Host warning to disallow UHF transmitter operation
VHF_OFF_EMER	Host warning to disallow VHF transmitter operation
PWR_OK	Host notification that previous warnings are rescinded

(Each of these three Alerts are periodically repeated until ACKnowledged by Host)


D2
D1
D3
D4
SMC
PWM
Battery
MCU
Solar Arrays
Partially Regulated Bus
Voltage, Current & Temperature sensors.
SMC
Fully Regulated Bus(ses)


Q1
D6
D8
D1
D2
D3
D4
D5
Q2
D7
Q3
MCU
1
PWM0
PWM1
Host COMM
BCR
Intercom
ON/OFF
ON/OFF
A/D Inputs
Q4
BCR A
P5
P6
P7
P8
P9
P10
P11
Load A
B
C
Solar
Panel
Inputs
A
B
C
D
TEMPERATURES
VOLTAGES
CURRENTS
+Bat Bus
BAT-A
Trickle
Charge
Commands,
Telemetry